Polar Vortex Reversal Experiment in a Rotating Shallow Water (Extended Abstract)

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Polar Vortex Reversal Experiment in a Rotating Shallow Water (Extended Abstract)

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Abstract: A rotating shallow water experiment with hemispheric beta effect was pursued. In the experiment, the steady planetary waves with zonal wave number one or two in initial westerly polar vortex are excited at lower latitudes. As a result of polar-ward propagation of the planetary waves, the initial polar vortex was reversed into easterly polar vortex at higher latitudes. One of experimental parameters is the Rossby number which was defined as the ratio of the strength of initial polar vortex to the system rotation. The larger value of the Rossby number had, the weaker reversal was happened, in both cases that the forcing wave number is one or two. In other word, the weak polar vortex is easily reversed, and the reversal of strong vortex is hard to happen. This property of the polar vortex reversal suggests a positive feedback mechanism which may explain the robustness of the Arctic Oscillation pattern with intra-seasonal, inter-annual and inter-decadal time scales. That is, in the negative (weak westerly) phase of the Arctic Oscillation, once the reversal would happen, the strength of the revived polar vortex would be small. Accordingly, the secondary reversal would happen much more easily. As a result, the negative phase of the Arctic Oscillation as a temporal mean state may have a tendency to be maintained. Vice versa, the positive (strong westerly) phase also may be maintained.

Introduction

"Arctic Oscillation (A.O.)" is interpreted as a surface signature of modulations in the strength of the polar vortex in winter-time. The positive polarity of the A.O. is a monthly mean state which is characterized by a strengthening of the westerly polar vortex from the surface to the lower stratosphere. The negative polarity is another phase which is characterized by weaker westerly polar vortex. The oscillation between these two phases can be seen in intra-seasonal, inter-annual and inter-decadal time scale (D.W.J. Thompson and J.M. Wallace (1998)). On the other hand, the "Stratospheric Sudden Warming (S.S.W.)" is a drastic dynamical phenomenon which is characterized by "Polar Vortex Reversal" in winter-time. This Reversal as renaming of the S.S.W. has also large inter-annual variation. In a winter, we may have S.S.W. once or more, but in another winter, we may have none.

In which polarity phase of positive or negative, the vortex reversal can be happened more easily and strongly? If the reversal would prefer the positive phase, the strengthened polar vortex would have larger possibility of break down. On the contrary, if it dislikes the positive phase, the westerly polar vortex may have tendency to be maintained. In order to find out the preference of the reversal, a laboratory experiment was devised and put into practice.

Experiment

Water as the working fluid occupies a vertical slightly elliptic cylinder with a thermally insulated convex parabolic bottom. The radiuses of major and minor axes are 147 ± 6 mm, respectively. The height and the base radius of the bottom are commonly 140 mm. The thickness of fluid layer has minimum value 140 mm at the center of the cylinder, and maximum value 280 mm beside the sidewall. The whole apparatus is rotated steadily about its vertical axis of symmetry at angular velocity Ω_1. This barotropic fluid system has hemispheric beta effect due to the gradient of thickness of fluid layer. The top and edge of the bottom correspond with the north-pole and the equator, respectively.

After the inner fluid motion is getting to solid rotation as same as the system, the rotating speed is abruptly reduced to Ω_2. Thus, the initial westerly polar vortex with the angular velocity Ω_2-Ω_1 is settled up. Simultaneously, the planetary waves with zonal wave number two are automatically excited due to the collision of fluid to the elliptic cylindrical sidewall. The inner fluid flow field at various levels were recorded by CCD camera and video recorder fixed on the rotating table. Since then, the time development of velocity field relative to the rotating system was analyzed. The Rossby number (Ro) is defined as $(\Omega_2-\Omega_1)/(2\Omega_2)$. Here, Ro is a experimental parameter which is the ratio of the strength of initial polar vortex to the system rotation. The case of larger Ro corresponds with positive phase of the A.O., and the smaller case corresponds with the negative phase. We pursued three experiments where $\Omega_1=30$ r.p.m. and Ro is 1/38, 1/18 or 1/10.

Next, a circular cylinder instead of the elliptic one was set up at the position where the axis of cylinder was slightly (7 mm) shifted from the axis of parabolic bottom but the axis of bottom was coincide with the system rotation axis. Thus, another series of experiments were pursued, where the planetary waves with zonal wave number one were excited.

Results

From the video image data which have been recorded, the tracers position vectors and its horizontal velocity vectors at each time were obtained by using a image processing technique. From the velocity vectors, the stream function was defined through the interpolation to grid point velocity fields.

Table 1 shows a set of several snapshots in the time series of contour map of stream function at upper level (260 mm height from the base) of fluid in the experiments with the elliptic cylinder. Here, time 0 means the time when the system rotation was reduced. At $t=10$s (which corresponds with about 4.5 day on the Earth), the initial westerly polar vortexes are deformed to elliptic shape. And several contours near the pole are separated into a pair of closed streamline circles, commonly in all cases of three kinds of Ro. At $t=20$s (9 day), we can see the beginning of invasion of anti-cyclonic vortex to the polar region, except for the case of the largest Ro. At $t=40$s (18 day), the closed anti-cyclonic stream lines near the pole are exposed, except for the largest Ro. That is, The initial westerly polar vortex had reversed into the easterly vortex. And the reversed polar vortex is accompanied by two cyclonic eddies which were separated from the initial polar vortex. In lower latitudes (near the sidewall), the westerly wind zone still be remained as similar as initial state. Until $t=160$s (72 day), we can see the easterly polar vortex,

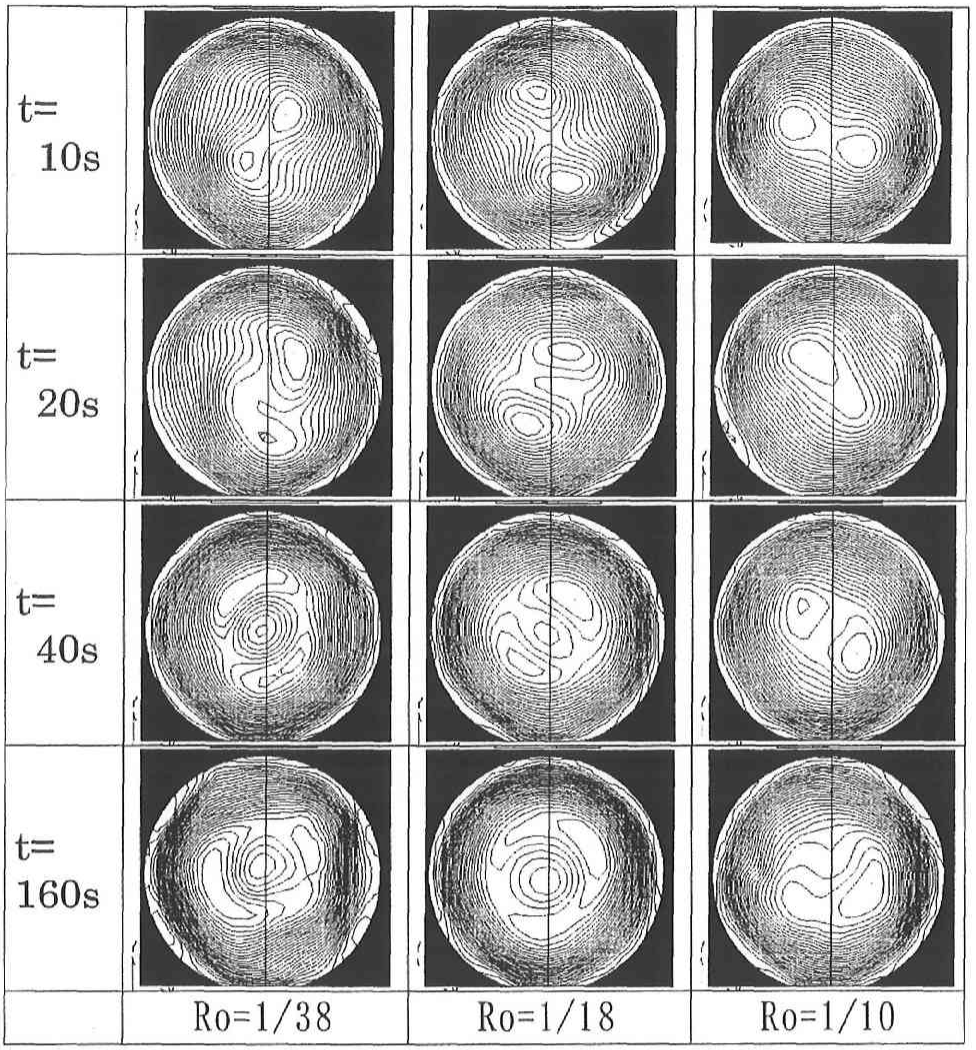

Table 1. time series of stream function in the case that forcing wave number is 2
The stream function at the upper level in the fluid is shown by contour map where *30* contours are drawn in any figures. Therefore, these figure show not magnitude of the flow but pattern of the flow. The close lines near side wall exhibit strong westerly flow.

although anti-cyclonic closed contour can not be seen in the case of the largest Ro.

Table 2 also shows snapshots of the flow field at the upper level in the experiments with the circular cylinder (the forcing wave number is one). At $t=15$s (6.75 day), the center of initial westerly polar vortexes are shifted from the pole, commonly in all cases of three kinds of Ro. At $t=30$s (13.5 day), we can also see the beginning of invasion of anti-cyclonic vortex to the polar region, except for the largest Ro. At $t=100$s (67.5 day), the closed anti-cyclonic stream lines near the pole are also exposed. Here also, we can see the reversal of the initial polar vortex. And the reversed polar vortex is accompanied by one deformed cyclonic eddy which was shifted from the initial position. In low latitudes, the westerly wind zone still be also remained. And

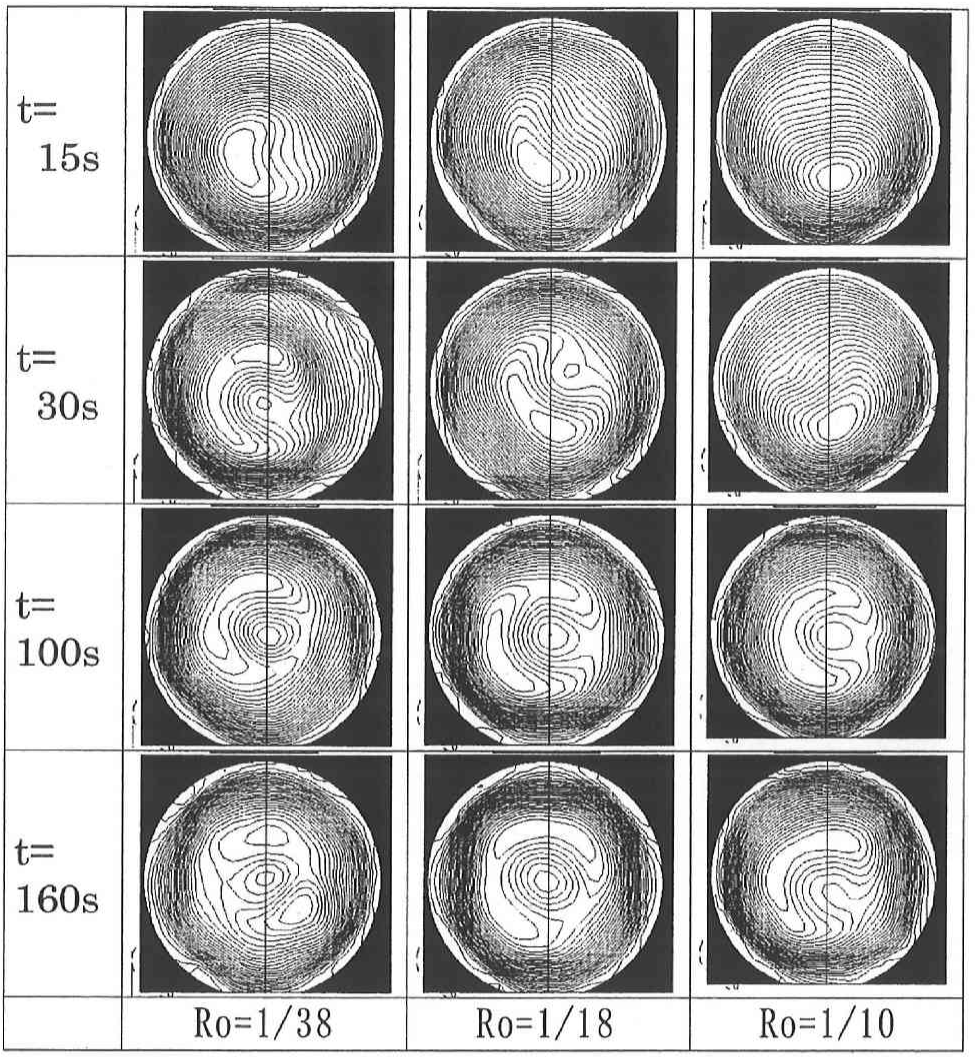

Table 2. time series of stream function in the case that forcing wave number is 1
As similar as table 1. except that the forcing wave number is one.

we can also see the easterly polar vortex until $t=160$s (72 day), although anti-cyclonic closed contour can not be seen in the case of the largest Ro.

In order to find the wave, zonal-mean flow interaction, the position and velocity vectors of the tracers were decomposed into its radial and azimuthal components. The horizontal plane in water tank is separated into ten coaxial annular regions. And the obtained velocity vectors were classified into ten groups so that all tracers of nth group locate in the nth circular channel region. In each channel, a distribution of the velocity vectors was fitted by using the Fourier series of azimuthal direction. Table 3 shows the time development of zonal mean angular velocity distribution in six kinds of combinations of experimental parameters. At higher latitude, it is found that the sign of zonal mean angular velocity is reversed from initial positive to final negative, in any case. In the case that Ro is 1/10, after the first polar vortex reversal, the

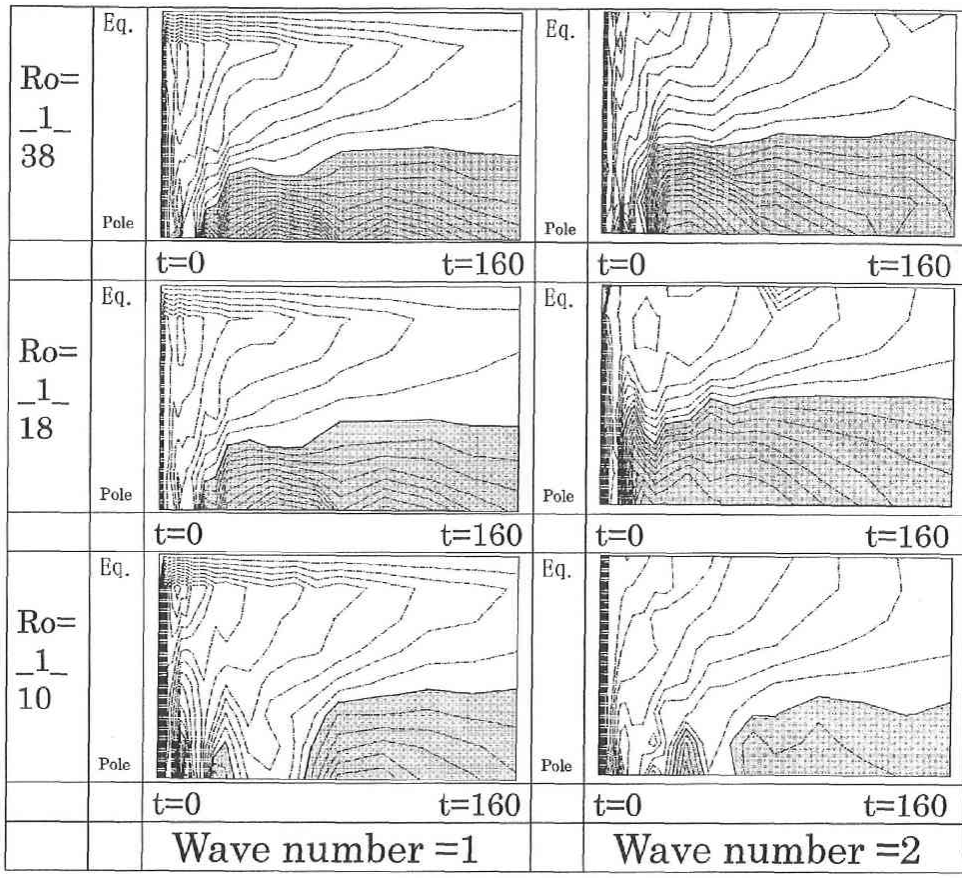

Table 3. time development of zonal mean angular velocity distribution
The zonal mean angular velocity is normalized by the strength of initial westerly polar vortex, and the increment of each contour is *0.1*. The shaded region shows negative sign. Although all regions have a long time tendency of decreasing of the angular velocity, we can see that the reversed vortex at higher latitudes continues to exist until the final stage.

restoration of westerly polar vortex can be seen, however, finally vortex at higher latitude settle down to the easterly, in both cases that the forcing wave number is one or two. In the case that *Ro* is 1/38, we can see the most wide and strong polar vortex reversal. After all, the larger value the Rossby number has, the weaker reversal is happened, in both cases that the forcing wave number is one or two.

Concluding remarks

It was found that the weak initial westerly polar vortex is easily reversed, and the reversal of the strong initial polar vortex is hard to happen, in our shallow water experiment. That is, the "Reversal" prefers the weaker polar vortex and dislikes the stronger polar vortex. Applying this result to real atmosphere, it is speculated that the S.S.W. (that is the polar vortex reversal) may occur frequently and strongly, in the negative phase of the A.O. more than the positive phase.

A phase of the A.O. is a temporal mean state averaged through one month or more long term. On the other hand, the "Reversal" is a phenomenon with shorter time scale.

This preference of the reversal make hit on an idea of positive feedback mechanism between the polar vortex and the reversal. In the negative phase of the A.O., once the reversal would happen, even if the westerly polar vortex would be restored through the way of the thermal process, the strength of the revived polar vortex would be small. Accordingly, the secondary reversal would happen much more easily. As a result, the negative phase of the A.O. as mean state may have a tendency to be maintained. Vice versa, in the positive phase of the A.O., the reversal is hard to happen. Accordingly, the positive phase also may be maintained. Thus, there is a possibility that the A.O. has two kinds of preferred mode which are the large amplitude positive and the large amplitude negative. Therefore, in the frequency distribution of the A.O. index, we may see, not the Gaussian which has one peak at mean value, but the double peaks at positive and negative values which correspond with the positive and negative polarities of the A. O., respectively. Hereafter, it may be necessary to analyze the real atmospheric data in such a point of view.

Reference

Thompson, D.W.J. and J.M. Wallace, 1998 : The Arctic Oscillation signature in the winter time geopotential height and temperature fields, *Geophys. Res. Lett.*, **25**, 1297-1300.